A fractional turn injector cyclotron*

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ABSTRACT

The emergence of the separated-sector cyclotron with its many desirable characteristics has created a pressing need for an accelerator which is suitably matched to it to serve as an injector. The 'fractional turn cyclotron' proposed here meets that need and at the same time avoids the disadvantages of d.c. injectors as well as the extraction and ion source accessibility problems of conventional cyclotrons. It consists of a cyclotron ion source, a simple magnetic field, and a multi-gap rf accelerating structure. The rf extraction from the ion source together with rf acceleration provide high current beam bunches properly synchronised for injection into the separated-sector cyclotron. The design also permits the use of low energy external ion sources, such as a polarised proton ion source. Preliminary design specifications of a 2 MeV injector for a 60 MeV separated-sector cyclotron are given.

1. INTRODUCTION

The invention of the separated-sector cyclotron (SSC) has removed the crowded and inaccessible central region of the sector-focused cyclotron and presented the accelerator designer with a number of alternative possibilities. The list of possible injectors includes: a d.c. accelerator with an rf beam buncher, a linear accelerator, and another cyclotron.

The choice of injector will of course depend on the design objectives. In the present case the objective is a versatile research accelerator which will produce high quality beams of protons, deuterons, ^{3}He and ^{4}He nuclei, and also intermediate mass ions. The energy is to be widely variable with the upper limit corresponding to 60 MeV protons. An energy gain of 30 then implies an injection energy of 2 MeV for protons. Versatility implies that there must be room for intermediate mass ion and polarised ion sources.

If the d.c. injector is single ended, then the ion sources must be at high potential, which limits access as well as the space available for the ion sources. If the d.c. injector is of the tandem type, then negative ion or neutral beams must be produced, which limits the versatility of the ion source. For any d.c.

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injector a variable frequency rf beam buncher must be designed in order to obtain pulsed current bunches synchronised for injection into the separated-sector cyclotron.

2. THE FRACTIONAL TURN CYCLOTRON

2.1. *General description*

The fractional turn cyclotron (FTC) proposed here avoids many of the disadvantages of the d.c. accelerator. It may be regarded as a linear accelerator to which a magnetic field has been applied, resulting in a curved path for the ions. Alternatively, it may be regarded as a cyclotron with the rf system operating on a high harmonic of the particle's angular frequency. The geometry of the FTC is illustrated in Fig. 1. Because the total angle through which the ion's velocity vector turns is less than 360°, extraction of the beam from the magnetic field is trivial. For the same reason the ion source is very accessible. In the example presented in Fig. 1 the *C* magnet has been restricted to 180° in order to make the assembly of the rf structure and the magnet particularly simple. They can be assembled separately and then slipped together.

2.2. *The rf structure*

The rf structure is shown in Fig. 2. It consists of two dee shaped horizontal plates mounted with their planes parallel and separated vertically by about 10 cm. The seven odd numbered drift tubes are attached to the upper dee, and the six even numbered drift tubes to the lower dee. The upper dee is supported by a dee stem which extends vertically upward and which is the centre conductor of a coaxial line. The lower dee has a similar dee stem extending vertically downward. The capacitance of each dee is resonated with the inductance of its shorted coaxial line. The resonant frequency is adjusted by moving the shorting plane along the coaxial line. In order to reach low frequencies without having excessively long coaxial lines, a conductor is inserted gradually between the dees increasing their capacitance to ground. The presence of a large transverse magnetic field allows the gap between adjacent drift tubes to be made small without undue danger of electrical breakdown between them. The first drift tube which also serves to pull the ions from the ion source may be constructed to have an adjustable length in order to be able to adjust the rf phase at which the ions pass through the rest of the rf structure. To accelerate protons to 2 MeV with 13 drift tubes requires a peak rf voltage in excess of 77 kV on the drift tubes.

2.3. *The magnetic field*

The trajectory illustrated in Fig. 1 assumes a uniform magnetic field. A *C* shaped *C* magnet (C^2 magnet) keeps the magnet coils and flux return path out of the way of the rf system. A field of about 2 kG is required to accelerate protons at 39 MHz on the twelfth harmonic. However, it will be seen later that a field of about twice this value is desirable for the acceleration of heavier ions. Since the trajectory is everywhere close to the centreline of the magnet, it will be altered only slightly if,

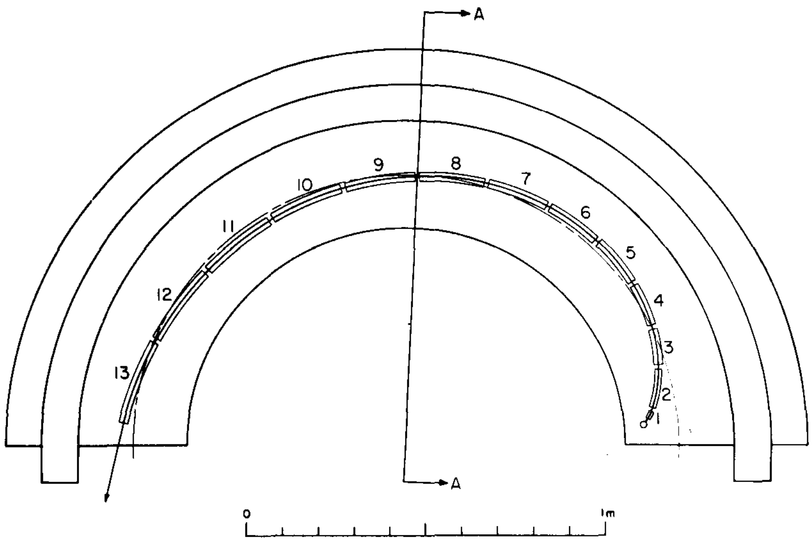

Fig. 1. Geometry of the fractional turn cyclotron. The trajectory of an ion in a uniform magnetic field is shown, assuming an energy gain E_0 upon entering and leaving each of the thirteen drift tubes. The length of each drift tube is 15° of orbit arc, which satisfies the cyclotron condition that the same length of time be spent in each drift tube. It should be noted that the entire orbit lies close to the semicircular centreline of the magnet. The even numbered drift tubes are driven 180° out of phase with the odd numbered drift tubes. Section AA indicates the view shown in Fig. 2.

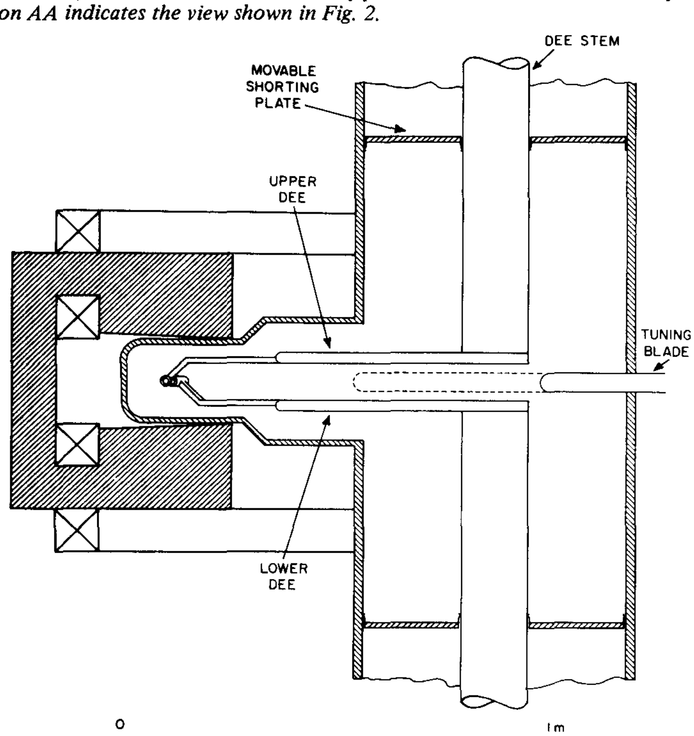

Fig. 2. A section view through the magnet, including a partial section of the rf system. Note that the magnet may be separated from the rest of the accelerator by sliding it horizontally. For clarity only two drift tubes are shown, one connected to each dee.

instead of a uniform field, the magnet has a field which decreases with distance from the magnet axis. Such a field would clearly provide magnetic focusing in both the vertical and radial directions. It only remains to choose the optimum value of $n = -(r/B)\,(dB/dr)$ for the magnet. The magnet gap has to be rather large, of the order of 20 cm, in order to allow sufficient separation of the dees for electrical insulation. Sector coils will be provided to make small adjustments in the magnetic field along the orbit, to insure that the orbit threads the drift tubes.

2.4. *The ion source*

Radio frequency extraction from a cyclotron type ion source provides the very high pulsed ion current needed for injection into the separated sector cyclotron. Ion sources of this type are capable of producing large currents of multiply charged ions. An average (not peak) current of 100 μA of He^{++} ions can be considered routine from such a source. Russian physicists at the Joint Institute for Nuclear Research have reported the following currents for ions accelerated in a cyclotron from an ion source which could be pulsed to a peak arc power of 40 kW: C^{4+}, 30 μA; N^{5+}, 20 μA; Ne^{4+}, 100 μA; Ne^{6+}, 1·2 μA; and Ar^{7+}, 5 μA. Due to the relatively large magnet gap and the fact that no orbits encircle the ion source, it is very accessible in the fractional turn cyclotron. It would be entirely feasible to install an ion source with a steady power input of 40 kW, if that should prove desirable. In addition to the cyclotron type ion source which would meet the needs for hydrogen ions, helium ions, intermediate mass ions and possibly also polarised ^3He ions, it should be mentioned that an external ion source (such as a polarised proton ion source) could be used with the FTC. All that would be required would be to replace the cyclotron ion source with some plates to produce an electric field to cancel the $V \times B$ field on the injected ions, until they reached the first drift tube.

3. THE ACCELERATOR–INJECTOR COMBINATION

3.1. *Radio frequencies*

There are many ways in which the radio frequencies may be chosen. However, it seems best to run both accelerators at the same frequency and to insist on a 3:1 tuning range for both. This choice allows the filling of every rf bucket of the

Table 1. INJECTOR-ACCELERATOR MODES OF OPERATION

Both the injector and the separated-sector cyclotron have a frequency range of 13 to 39 MHz. They always operate at the same rf. 'Harm.' is the ratio of the rf to the orbital angular frequency. The two dees (called deltas) in the separated-sector cyclotron have an orbital length of 40°. 'Drift tube length' and 'delta length' give the rf phase angle change during a transit of the accelerating electrode.

		Injector (FTC)		*Accelerator (SSC)*		
Energy/ nucleon MeV	Freq. MHz	Harm.	Drift tube length	Harm.	Delta length	Delta efficiency
6·7–60	13–39	12th	π	4th	160°	98·5%
0·7–6·7	13–39	36th	3π	12th	480°	86·6%

accelerator and places no practical restriction on the lower energy limit of the combination. Table 1 shows the high and low energy modes of operation, the division occurring at 6·7 MeV per nucleon.

3.2. *Hydrogen and helium isotopes*

It is expected that the major portion of the demand will be for accelerated beams of hydrogen and helium isotopes. The output energy of the separated-sector cyclotron is to be limited only by the magnetic field so that the output energy will be approximately $60(q^2/A)$ MeV where q is the charge state and A is the nucleon number of the ion. An energy gain of 30 is planned for the separated-sector cyclotron, so the injector is required to produce an energy of $2(q^2/A)$ MeV.

3.3. *Intermediate ion capability*

This type of injector-accelerator arrangement holds considerable promise for the acceleration of intermediate mass ions for three reasons. First, as has been discussed, cyclotron type ion sources are capable of producing good sized currents of multiply charged ions. Second, since the injector magnetic field required for full energy protons is small (0·2 Wb/m^2 in the example given), it is reasonable to increase this field a factor of two or more for the acceleration of heavier ions. Third, the charge state of the ion may conveniently be changed by gas or foil stripping at a double focus between the injector and the separated-sector cyclotron.

If the magnetic field of the injector can be set at twice the value required for 2 MeV protons, then the magnetic limit for the output energy of the injector becomes $8(q^2/A)$ MeV. If the electrode voltage is capable of accelerating 2 MeV protons, then the accelerating voltage energy limit is $2q^2$ MeV. It is of course

Table 2. INTERMEDIATE ION CAPABILITY

The initial ion, its charge state and expected current are given. The expected stripping efficiency for the final charge state is specified as well as the final energy. The foil stripper would be located at a double focus between the two accelerators. 'L' marks the energy limiting accelerator.

Initial ion	*Expected current* μA	*Injector energy* $\leqslant 8(q^2/A)$ $\leqslant 2q$ MeV	*Final charge state*	*Stripping efficiency* %	*Final energy* $\leqslant 60(q^2/A)$MeV
$^{6}Li^{+}$	?	1·3L	3+	37	40
$^{6}Li^{2+}$	8	3·0	3+	73	90L
$^{9}Be^{2+}$	?	3·5	4+	25	106L
$^{9}Be^{3+}$	2	3·5	4+	25	106L
$^{12}C^{4+}$	30	4·2	5+	17	125L
$^{12}C^{4+}$	30	6·0	6+	2	180L
$^{14}N^{5+}$	20	5·1	6+	9	154L
$^{14}N^{5+}$	20	7·0	7+	1	210L
$^{20}Ne^{4+}$	100	6·4	8+	3	192L
$^{20}Ne^{4+}$	100	8·0L	9+	0·7	240
$^{40}Ar^{7+}$	5	5·0	10+	1	150L

advantageous to strip electrons at as high an energy as possible. However, for the combination presented here stripping always occurs at 1/30 of the final energy. Table 2 lists some of the intermediate ion capabilities of this combination. The expected ion source currents are based on cyclotron accelerated ion currents of the charge state listed, as quoted in the literature.[1] The stripping efficiency is based on the equilibrium charge state distribution curves for ions passing through foils computed by Zaidins.[2] Examination of these curves indicates that an accelerator designed primarily for heavy ions should have a lower energy gain and a higher energy injector, or should consist of an injector followed by two successive separated-sector cyclotrons with additional stripping between the cyclotrons. However, very good intermediate ion performance can be achieved with the relatively modest injector-accelerator combination discussed here, thus increasing its versatility.

4. CONCLUSION

While the fractional turn cyclotron has been discussed in the context of a particular set of design objectives, it should be recognised that many other variations are possible. For example, a simple low energy version with only one or a few drift tubes could be used as an rf synchronised source of multiply charged ions of about 1 MeV energy. Conceivably, such a source could even be located in the terminal of a large tandem accelerator which in turn injected into a separated-sector cyclotron.

Because cyclotrons have much more in common with other cyclotrons than do d.c. accelerators, they need to be given adequate consideration when an injector for a separated-sector cyclotron is being selected.

DISCUSSION

Speaker addressed: W. R. Smythe (Colorado)

Question by M. Reiser (University of Maryland): What is the advantage of adding the magnet rather than building a straight linac with quadruple focusing?
Answer: This system provides double focusing in a way which is nicely compatible with the rf structure. At these frequencies the drift tubes are too small to accommodate the quadrupoles.

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